J Radioanal Nucl Chem (2014) 301:629–639
DOI 10.1007/s10967-014-3260-5

A review of conventional explosives detection using active neutron interrogation

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Received: 8 May 2014 / Published online: 22 June 2014
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Abstract Conventional explosives are relatively easy to obtain and may cause massive harm to people and property. There are several tools employed by law enforcement to detect explosives, but these can be subverted. Active neutron interrogation is a viable alternative to those techniques, and includes: fast neutron analysis, thermal neutron analysis, pulsed fast/thermal neutron analysis, neutron elastic scatter, and fast neutron radiography. These methods vary based on neutron energy and radiation detected. A thorough review of the principles behind, advantages, and disadvantages of the different types of active neutron interrogation is presented.

Keywords Explosives · Neutrons · Fast neutron analysis · Neutron activation analysis · Neutron scatter · Measurements

Introduction

A quick, accurate method of finding hidden explosives is a high priority in national security. Relatively small amounts of explosive materials in airport luggage or landmines can cause destruction of property and injury or death to individuals. Various detection methods from different fields of science, including vapor detection and X-ray screening, have been employed in order to identify explosive materials [1–5]. However, it has been only during the last 25 years or so that neutron interrogation has become a viable method of identifying potential explosive materials [6]. This paper will review the advantages and disadvantages of neutron interrogation as a means of explosives detection as well as provide a brief overview of the various types of neutron sources and related information. Then, several techniques that use neutrons to identify explosives will be discussed in greater depth. These will include thermal neutron analysis, fast neutron analysis, pulsed fast/thermal neutron analysis, neutron elastic scatter or fast neutron scattering analysis, and fast neutron radiography.

The explosives interrogation methods that do not involve neutrons all have drawbacks that limit their effectiveness. Many methods, including the use of canines, ion mobility spectrometry, and chemiluminescence, search for trace amounts of explosives in the air [7–9]. Unfortunately, if the explosives are properly handled and sealed, these techniques will be unable to identify the material. There are also detection methods that involve the use of x-ray transmission or photon scatter to investigate targets [3, 10–12]. However, these photons can be shielded using high atomic number materials, which would allow anything behind the shielding to remain undetected [13]. Furthermore, although densities and atomic numbers can be approximated using these methods, they cannot be specifically determined [14]. This allows for confusion when examining objects. A harmless material with physical properties similar to that of an explosive will trigger a false alarm. More importantly, depending on the orientation of materials inside the object, it is still possible that explosive material could be misidentified as harmless.

There have been many specific methods proposed that use a neutron source to search for explosives, but the active interrogation techniques these systems employ are generally the same. In passive interrogation, the system does not interact with the target and only uses information that can

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be obtained without invasive measures, such as when a canine unit sniffs the air around the outside of a target. With an active interrogation system, the explosives detection system is actually interacting with the target, such as by directing neutrons towards it, in order to obtain information more quickly. Each of the systems discussed in this paper requires neutrons to interact with the materials of interest in some specific target. Depending on the concentration and neutron interaction cross sections of the atoms present in the target, the neutrons have a greater or lesser chance of interacting and releasing radiation [15]. Radiation associated with these neutron interactions includes characteristic X-rays, gamma rays, inelastically scattered neutrons, and elastically scattered neutrons [16]. The active neutron interrogation systems have detectors set up to record one or more types of secondary radiation. The signal is then processed by the equipment and analyzed either by a computer or a person. This assists the operator in determining whether the target needs to be investigated further to see if the materials within it are either illegal or dangerous.

The major advantage of neutron based explosive detection systems is that it is hard to shield neutrons, which pass through iron and lead with very little attenuation. This is a benefit compared to many other systems, most notably those based on x-rays and gamma rays directed at the target, which can be shielded by middle to high atomic number, dense materials. If such materials are placed between the source and explosive, the explosive may not be detected. However, neutrons, which are better shielded by light nuclei, pass through high atomic number materials and reach the explosive. Another disadvantage of x-rays and gamma rays are that they can only broadly discriminate between organic and inorganic materials while neutrons are effective at differentiating between various types of organic material based on their chemical composition [17].

The fact that neutrons are tough to shield may make them advantageous for detecting explosives, but it also causes them to be a hazard to work with. Neutrons can deliver a potentially harmful radiation dose to nearby personnel if the individuals are not properly protected. The difficulty of attenuating neutrons requires either significant shielding or large stand-off distances. Either option contributes to an expanded system footprint. This can make implementation for luggage inspection at airports and cargo inspection at shipping yards, both places where floor space is at a premium, complicated. Similarly, neutron sources used in land mine detection would necessitate shielding, which adds weight to the system and limits its portability. Furthermore, the additional shielding material adds to the system cost. When implementing on a large scale, these costs can be significant.

Another disadvantage of neutron interrogation is the potential for materials activation. When high energy neutrons interact with certain atoms, it is possible they will undergo a reaction and leave the target atom in an excited state. Eventually this atom will move to a more stable nuclear state and release radiation. This may happen almost immediately after the neutron interacts with the atom, or it may be delayed, such as with activated silicon and phosphorous [18]. Due to the fact that the materials being interrogated are largely unknown, it is impossible to anticipate what interactions will occur and the amount of activation induced. Therefore, it is necessary to strike a balance between having a high enough neutron flux to obtain a clear signal, while keeping it low enough to minimize the risk due to activation.

A final disadvantage is the novelty of the systems proposed. Research and development is continuing in the field of active neutron interrogation in a number of areas, but there has yet to be a system that has found wide spread deployment. This means data and benchmarks are either being generated in a lab or at one or two trial locations. Conversely, metal detectors and x-ray screening, for example, have been used for decades in airports, courthouses, and other public areas around the world. They are mature, robust technologies with a proven track record. Any new approach must provide a distinct advantage or address a unique need to be considered for wide scale adoption. Active neutron interrogation may be a viable alternative to other explosive detection techniques, but its pros and cons must be weighed carefully when compared to competing technologies.

Basic principles of neutron-based explosives interrogation

Neutron sources

There are four basic types of compact neutron sources. The first is a radioactive material that spontaneously and continuously releases neutrons as it decays to a more stable state. An example of this would be ^{252}Cf, which has a neutron energy spectrum with a most probable energy of 0.7 MeV and average energy of 2.1 MeV. Another neutron source type pairs two nuclides: one alpha-emitting, and another that absorbs the emitted alpha particle and then releases a neutron. These sources include plutonium beryllium (PuBe), americium beryllium (AmBe), and americium lithium (AmLi). Due to the variability of the alpha particle energy, the resultant neutron energy spectra are quite broad and dependent on the alpha source [19]. A third neutron source depends on a high energy photon to excite a nucleus resulting in the release of a neutron. The

two nuclides that typically undergo this reaction are ^{9}Be and ^{2}H. The minimum photon energy for these reactions is 1.67 and 2.23 MeV, respectively. Typical sources of gamma rays include ^{226}Ra, ^{124}Sb, ^{72}Ga, ^{140}La, and ^{24}Na. An advantage of neutron sources that use high energy photon excitation is that the resultant energy of the neutron is dependent on the energy of the incident gamma ray. If a monoenergetic photon source is used, a nearly monoenergetic neutron source will be obtained. However, the photoneutron interaction probability is relatively low. Therefore, a high activity gamma ray source must be used, which will create a large gamma ray background for any measurements [19].

All of these types of neutron sources are easy to operate and require no equipment other than shielding. The associated major drawback is that they are constantly decaying and there is no way to turn them "off." Therefore, when the neutron source is unshielded, it presents a constant hazard to nearby personnel, even when it is not being used. Furthermore, the radioactive material can expose unknowing individuals to a constant radiation dose if it is lost or stolen. The sources themselves present possible risks for terrorism when coupled with conventional explosives to create radiological dispersive devices.

Neutron generators, however, are a viable alternative to radioactive sources. These are systems that do not rely on radioactive material. Instead, they enable reactions that lead to the creation of neutrons. They allow for timed neutron pulses, can be turned off and thus are easier to transport, and have high neutron fluxes [20]. One example of such a generator is the deuterium–tritium (D-T) neutron generator. When a D-T generator is turned on, deuterium (^{2}H) ions are accelerated across a maximum voltage difference of around 90 kV into a tritium (^{3}H) target. The deuterium and tritium undergo a fusion reaction to form an alpha particle (^{4}He) and a neutron whose average energy is near 14.1 MeV [19]. A deuterium–deuterium (D–D) neutron generator works in the same way, except in this case deuterium ions are accelerated towards a deuterium target. When the two particles go through a fusion reaction, the product is ^{3}H and a neutron with an average energy of about 2.5 MeV. In both cases, if the generator is off, the deuterium is not directed towards the tritium or deuterium and no neutrons are created. This makes it ideal for interrogation applications and reduces the risk of accidental exposure from the unshielded source. Several compact D-T and D–D generators have been designed specifically for active neutron interrogation applications [21]. For both radioisotopes that release neutrons and neutron generators, the energy of the neutron is dependent on the atom that is decaying or the reaction taking place. Both of these types of sources tend to have very specific neutron energies that cannot be easily adjusted. Large accelerators, which are costly and complicated, can be used to impart the incoming deuterium ion with more energy than required to initiate fusion, resulting in some of the excess energy being transferred to the resultant neutron in the D–D or D-T reaction [22, 23]. Alternatively, the neutrons can be passed through a moderating material so that they lose energy through multiple interactions with nuclei of low atomic mass. This will generally lower the average energy of the neutron to the thermal range around 0.025 eV, but cannot reliably reduce a significant number of neutrons to any other energy.

Table 1 Summary of types of neutrons sources with advantages and disadvantages for use in active neutron interrogation systems for conventional explosives

Neutron source	Examples	Advantages	Disadvantages
Fission	^{252}Cf	Small	Can't be turned "off"
		Relatively inexpensive	Not monoenergetic
(α, n)	Am/Be, Pu/Be	Small	Can't be turned "off"
		Relatively inexpensive	Not monoenergetic
Photonuclear	^{9}Be or ^{2}H	Can be nearly monoenergetic	Can't be turned "off"
	With ^{24}Na, ^{28}Al, or ^{38}Cl	Small	High gamma ray background
		Relatively inexpensive	
Fusion generator	D–D, D-T	Can be nearly monoenergetic	Expensive
		Can be turned off	Associated electronics make it larger than other sources

All of the neutron sources have their own advantages and disadvantages, which are summarized in Table 1. It is up to the system designer to decide which best suits his or her needs while adequately limiting the potential dose to any operators or the nearby public.

Neutron source collimation

Regardless of the type of neutron source, the distribution of neutrons is either isotropic or nearly isotropic. This is not ideal for the application of neutron interrogation where the operator is interested in neutrons interacting in a target within a specified solid angle. If the source were unshielded and neutrons were released isotropically to interact with the surrounding environment, products of the interactions, either scattered neutrons or associated gamma rays, could end up being directed towards the detector and counted by the detection system. These additional interactions in the detector create noise and the signal from the materials being investigated may be lost or obscured. Furthermore,

the additional neutrons provide a health hazard to anyone near the source. Shielding can be used to limit the isotropic neutron source, reduce the unwanted interactions, and protect nearby personnel and the public [24, 25]. Such shielding, applied to either radioactive sources or neutron generators, is never completely effective so there will still be some neutrons that escape the collimation and interact within the environment. In the case that additional shielding is too heavy or has too large of a footprint, another option is to use associated particle imaging (API).

Associated particle imaging

Without bulky collimation, it is very hard to determine if a detected gamma ray or neutron is the result of neutrons scattering in the environment or within the target. Additionally, even if it can be determined that the neutron interacted in the target, it is unknown whether the secondary radiation is a result of a single interaction or several based on the detector signal alone. The incident neutron may undergo many interactions within the target and change its energy before scattering out or creating a prompt gamma ray. This can lead to much uncertainty within the system. One way to help correct this is to use associated particle imaging (API) [26, 27]. This system includes a fusion source, either D-T or D–D. When the interaction occurs in the source and creates an energetic neutron, the associated charged particle, which moves in the opposite direction of the neutron due to conservation of momentum, is detected. The time and angle at which the charged particle is detected signals the time of creation and resultant incident angle of the neutron. If the neutron is not directed toward the target, any secondary radiation detected is ignored by the system [28]. If, on the other hand, the initial neutron is directed at the target, then the time until the secondary prompt gamma ray or scattered neutron interacts within the detector is used to determine whether the neutron interacted once, in which case it is counted by the system, or multiple times, for which it is neglected. The total time of flight of the neutron can also be used to determine its energy. The additional information helps to reduce sources of uncertainty in the explosive detection system. Portable neutron imaging devices have been developed with yields of at least 1×10^8 neutrons per second and weighing 12 kg, which could prove useful for many explosive detection scenarios [21].

Explosive detection methods

In order to find explosives, active neutron interrogation methods rely on identifying the signature chemical makeup that most explosive materials possess. Many of the commonly used explosives have high nitrogen content [29]. This relatively large amount of nitrogen, compared to other elements common in explosives, such as hydrogen, carbon, and oxygen, is what neutron based detection systems look for [16]. The abnormally high nitrogen content is used as a flag when searching for explosives. Some of the explosives that can be detected are trinitrotoluene (TNT), cyclotrimethylenetrinitramine (RDX), ammonium nitrate, composition 4 (C-4), pentaerythritol tetranitrate (PETN), and Semtex 1A [30, 31]. Unfortunately, not all explosives are rich in nitrogen, such as triacetone triperoxide (TATP), which has been used by several terrorist groups, including shoe bomber Richard Reid in 2001 [32]. Furthermore, many other items of concern, such as guns and knives, would go undetected by all active neutron interrogation methods besides neutron transmission. Additionally, benign materials, such as rubber, silk, and nylon, may have high nitrogen content that could trigger false alarms [33].

Although they are unable to detect all types of explosives, systems employing the various active neutron interrogation methods can be used in a wide array of applications. Their ability to detect both small and bulk explosives means they can be deployed to search automobiles and cargo containers. They can also be used for baggage and freight inspection at airports [34]. There is also ongoing research exploring usage of these systems to search for land mines and roadside improvised explosive devices (IEDs). Narcotics and chemical agents, which are additional contrabands of interest to border security officials, also contain relatively high nitrogen levels or specific carbon to oxygen ratios and can be readily identified using neutron interrogation [18, 30].

Neutron-based explosive interrogation systems

There are several different types of active neutron interrogation methods, each with its unique advantages and disadvantages. The various methods are summarized in Table 2. The system designer must decide what elements he or she wants to search for and how high their associated neutron flux can be, then determine the best method to fit these requirements. The section will review such systems.

Thermal neutron analysis (TNA)

Thermal neutron analysis (TNA) takes advantage of the characteristic radiation released by activated nuclei [6]. In this method, thermal neutrons, with energy around 0.025 eV, are used. While some of these passing through the object do so without interaction, others are absorbed through a characteristic (n, γ) reaction with nuclei within the target. The new nuclides created in the absorption process are placed in an excited state. In order for the

Table 2 Summary of active neutron interrogation methods and their advantages and disadvantages for conventional explosives detection

Active neutron interrogation method	Advantages	Disadvantages
Thermal neutron analysis (TNA)	Detects nitrogen and hydrogen	Does not detect carbon or oxygen
	Higher interaction probability than FNA	
Fast neutron analysis (FNA)	Detects nitrogen, carbon, and oxygen	High neutron background
	Neutron moderation not required	Relatively low fast neutron interaction cross section
Pulsed fast/thermal neutron analysis	Detects hydrogen, carbon, nitrogen, oxygen, chlorine, silicone, and phosphorous	Lower interaction probability than NES
	Low neutron background compared to TNA and FNA	
Neutron elastic scatter (NES)	Higher interaction probability than neutron absorption	Determination of neutron energy is more complicated
	In theory, can detect all low atomic number elements	Can only detect low atomic mass nuclides
	Low neutron background	
Neutron transmission/fast neutron radiography	Lower flux necessary since transmission is likely	Requires neutrons of various energies

nuclei to move back down to a more stable state, they release a gamma ray with a characteristic energy dependent on the nuclei absorbing the neutrons. By using a spectroscopic gamma ray detector, the relative amounts of each of these elements can be determined by looking for these unique characteristic energy peaks in the gamma ray spectra. Generally, a high peak at nitrogen's characteristic energy is used separately, or in conjunction, with other flags to signal the presence of suspicious material.

The theory of TNA for explosives detection has been around since the 1980s and several systems have been designed to use it to search for explosives [6, 35–37]. TNA primarily searches for nitrogen and hydrogen, because when these nuclei absorb a thermal neutron, they emit a 2.2 and 10.8 MeV gamma ray, respectively [38]. Originally developed as a means to detect most solid explosives, TNA has also been applied to the detection of drugs, liquid explosives, and buried land mines due to its ability to also detect chlorine [36, 37]. More recently, the relative amounts of hydrogen, carbon, and nitrogen were determined for various samples when placed in a beam of thermal neutrons from a research reactor [39]. An explosive detection system for small packages was created which employed TNA. In tests, the system was able to determine 1.0–0.1 L of concealed liquid explosives and chemical weapons threats 90 % of the time and provided false alarms 1 % of the time with measurement times of 60 s. Also, the system was able to distinguish between live and inert explosive ordinances 100 % of the time employing measurement times of 60 s [40].

A pulsed TNA device is being developed which uses graphite to moderate the neutrons of a pulsed D-T generator until they reach thermal energies. Once the thermal neutron flux is sufficiently characterized, it should be possible to determine the chemical makeup of materials and detect explosives using multiple thermal neutron pulses. Additionally, the detectors will also have the ability to detect fast neutrons, which will allow the system to search for fissionable materials once the thermal neutrons induce fission [41].

TNA has proved an effective detection method. It is employed in a commercial system for determining the location of anti-tank mines [42, 43] and more recently, land mines and other explosive remnants containing as little as 20 g of hydrogen [44]. Although the cost and time required using TNA for demining is increased compared to more conventional methods, it can be justified for more complicated situations such as important infrastructure and industrial areas [33]. It was shown that replacing a ^{252}Cf source and moderator with a D-T source and moderator improved the TNA method for landmine detection both for deeper mines and when the system is not directly over the mine [45].

Fast neutron analysis (FNA)

One improvement to the previous method is to increase the energy of the neutrons in a technique known as fast neutron analysis (FNA) [29]. Instead of relying on thermal neutron absorption like TNA, FNA exploits the inelastic scatter of fast neutrons off characteristic nuclei such as nitrogen, oxygen, and carbon. The ratio of these three elements in explosives is quite specific [38]. For an inelastic collision, when the fast neutron is incident on the nucleus, it bounces off with a lower energy and is accompanied by a characteristic gamma ray. The cross sections for inelastic scatter vary by nuclei as well as neutron energy and are generally smaller than cross sections for thermal neutrons, meaning fewer interactions per unit flux [38]. A collimated beam of fast neutrons is directed at the target. By comparing the relative numbers of detected characteristic gamma rays, an operator or automated computer program can make a determination as to whether the target constitutes a threat. If the characteristic gamma rays are detected in ratios similar to conventional explosives, a red flag is raised and the package can be examined more thoroughly. As an

example, FNA was used in a prototype system that was remotely controlled and employed a D-T generator and high-purity germanium detectors to interrogate vehicles for IEDs [46].

Furthermore, researchers have investigated FNA for use in conjunction with coded aperture imaging to examine airport luggage and cargo containers. Coded aperture imaging works by placing shielding material over specific parts of the detector. Gamma rays interact with the detector after having passed through the unshielded part of the aperture. Given the pattern of the interactions on the detector and the configuration of the aperture, it is possible to determine the distribution of the source within a volume [47]. Instead of a narrow beam of neutrons, this method uses a field of fast neutrons that interact throughout the item of interest simultaneously. The neutrons undergo an inelastic scattering interaction within the target and create characteristic gamma rays. Theoretically, by using coded aperture imaging, the system is able to determine the location of the interaction and therefore, the elemental makeup of specific regions within the target. The method is able to determine the mass of a sucrose sample to within 7 % and determine its molar ratio of carbon to oxygen to within 4 %, but needs further investigation for use in high background and three-dimensional applications [48].

This method has an advantage over TNA because more of the elements present in explosives emit characteristic gamma rays during FNA. For TNA, the process usually just looks for high nitrogen content and hydrogen, but with FNA, the signal also includes information about the concentration of oxygen and carbon, which have unique concentrations relative to one another and nitrogen in explosives. Therefore, the additional information gained through FNA can be used to eliminate some of the false alarms associated with TNA [3].

One major drawback to this method is the large background noise associated with FNA [29]. The fast neutrons, once scattered, can interact within the gamma ray detectors and distort the gamma ray signal coming from the target. It is possible to shield these neutrons, but the detector efficiency must be sacrificed. One way to limit the fast neutron background is to use associated particle imaging. This method has allowed for preliminary detection of underwater TNT [49]. Another option is to use a pulsed beam of fast neutrons, as described in the next sub-section.

Pulsed fast neutron analysis (PFNA) and fast/thermal neutron analysis (PFTNA)

To reduce the background signal in FNA, the fast neutrons are released in short pulses in an approach termed pulsed fast neutron analysis (PFNA). Gamma rays traveling at the speed of light move about seven times faster than the neutrons used in PFNA, in which 8 and 14 MeV neutrons have velocities of 3.9 and 5.2 cm ns^{-1}, respectively [50]. Releasing the neutrons in short pulses allows for any gamma rays that are created during an inelastic collision to reach the detector before the scattered neutrons that accompany them. The gammas rays from the target are counted first, and when the neutrons interact later within the detector and create additional gamma rays, the system discriminates and neglects them. Recently, hydrogen, carbon, and oxygen concentrations were determined in a variety of materials of interest using a 14 MeV PFNA source and a $LaBr_3$:Ce detector [51]. Additionally, Compton cameras have been investigated for use in PFNA to determine the elemental compositions at a localized point within the target [52]. Compton cameras, originally used with gamma ray astronomy and medical imaging, detect the Compton scatter of a photon on one plane of a detector, and the photoelectric absorption of the same photon on another. Given the angle of scatter and final energy of the photon, the incident angle of the photon can be resolved. With enough events, the source of the photons can be determined [53].

After the fast neutrons interact in the target, some of them become thermalized through multiple interactions [38]. These thermal neutrons can then be absorbed in the nitrogen nuclei, just like in TNA, and release characteristic prompt gamma rays that are then recorded. Fast/thermal neutron analysis (FTNA) takes advantage of the already preset thermal neutrons to obtain more information about the object being interrogated. FTNA, combining the principles of PFNA and TNA, performs the equivalent of two separate interrogations at once, looking for both characteristic neutron absorption and neutron inelastic scatter gamma rays. Furthermore, the neutron generator can be cycled in such a way to allow for neutron thermalization between pulses. This is known as pulsed fast/thermal neutron analysis (PFTNA). In this case, the target is hit with fast neutrons for about 10 μs and the gamma rays from the inelastic fast neutron collisions are detected, similar to PFNA. The generator is turned off for 90 μs while the neutrons from the initial pulse thermalize within the target. Some of these thermalized neutrons are absorbed by nitrogen, hydrogen, and chlorine nuclei in the target and characteristic gamma rays are released. This cycle is repeated for a set number of times. Finally, the sample is allowed to sit for an extended time period while any characteristic gamma rays from previously activated nuclei with slightly longer half-lives, such as silicon or phosphorous, are released [18]. The combination of multiple detection techniques in PFTNA assists in determining the composition of the target. The relative amounts of carbon, oxygen, and nitrogen can be obtained with PFNA; the presence of nitrogen, hydrogen, and chlorine in the target

can be determined with TNA; and by looking for delayed gamma rays, silicone and phosphorous can also be detected. This in turn helps the operator make a more accurate determination of the unknown material within a package and assess whether or not it is a threat.

Many advances have been occurring in the fields of FTNA and PFTNA. Preliminary tests have shown the ability of an FTNA detection system to correctly determine gamma ray signatures of nitrogen rich targets as small as 3.8 L when compared to inert targets [54]. A handheld PFTNA system was developed and tested using a 14.1 MeV D-T neutron generator that determined the elemental content of packages in field demonstrations [55]. It correctly verified the carbon to oxygen and nitrogen to oxygen ratios to within a few percent for C-4, TNT, and RDX explosives. Also, the use of PFTNA was investigated for the interrogation of larger objects, such as cargo containers [18], while other researchers have attempted to design a CsI(Tl) detector that will be able to provide a multi-color picture of the object during PFTNA [56]. Using PFTNA, researchers have shown it is possible to find 2 kg of cocaine hidden behind 85 cm of cement [57]. More recently, a PFNA system was deployed in an airport in Houston, Texas. It uses a Van de Graaff accelerator to obtain neutron pulses on the order of several nanoseconds for time of flight information and is able to obtain three-dimensional images of airplane cargo containers [58]. Finally, artificial neural networks have been applied to help in identifying explosives from gamma ray spectra [59].

Fast neutron scattering analysis (FNSA) or neutron elastic scatter (NES)

Another detection technique is fast neutron scattering analysis (FNSA) or neutron elastic scattering (NES). Many explosives have a chemical signature that is high in nitrogen and contains carbon, oxygen, and hydrogen. All of these elements have a relatively low atomic mass, which allows for a neutron to transfer a substantial amount of energy during an elastic collision. In elastic collisions, when the neutron interacts with a nucleus it immediately transfers energy as it bounces off. If the initial energy of the neutron is known, and if both the neutron's scattering angle and scattered energy are determined by detectors, then the mass of the nucleus can be calculated [38]. The common elements in explosives have nuclei with different masses. Therefore, by using this method the relative amounts of each element can be determined based on the energy and angle of scatter of the detected neutrons.

The benefit of this technique is that for most nuclides, the probability of elastic scatter is larger than either inelastic scatter or neutron capture. This allows for a stronger signal at lower flux, reducing the activation and required shielding. This method requires the ability to determine the energy of a scattered neutron, but the energy discrimination for neutron detectors is not nearly as good as gamma ray detectors. However, NES does show promise. Experimentally, it was shown that atom fractions of a small sample between 0.2 and 0.8 kg could be determined [60]. Also, computer simulations were run that helped characterize the scattering of fast neutrons in explosive materials [61]. If this detection method can be further improved, it would allow for explosives detection in airports or when searching for land mines [62].

Neutron transmission/fast neutron radiography

Because neutron attenuation varies based on neutron energy and the materials they are passing through, their transmission through a target reveals some unique information about the elemental makeup. Using a ^{252}Cf source, it is possible to search for nitrogen and oxygen in the target. Both of these elements have neutron absorption resonances and the energy spectrum of the transmitted neutrons will show a decrease at these resonance energies compared to a sample that contained no nitrogen or hydrogen [63]. Also, looking at the ratio of fast neutron transmission to gamma ray transmission can help provide an idea as to the type of material in a target air cargo container [64]. This method allows for the determination of the density of materials as well as their class of composition: organic, glass or ceramic, or metal.

One of the advantages of neutron transmission is that it does not require a strong source because it is looking for neutrons that do not interact in the target. Since neutrons tend to have a relatively low interaction probability, most of them will pass through the target and contribute a signal to the system [63, 65]. However, neutron transmission cannot identify as many elements as some other active neutron interrogation methods and traditionally only determined high concentrations of certain elements, such as nitrogen.

More recent advances in neutron transmission, known as fast neutron radiography, have shown promise. By combining neutron and gamma ray transmission, fast neutron/gamma ray radiography can determine the average composition of an unknown target material. This is either accomplished using separate compact D–D or D-T sources for the neutrons and a ^{60}Co source for the gamma rays, or a high-energy accelerator that pulses both particles [65]. Alternatively, a variable-energy, quasi-monoenergetic neutron source can be employed to interrogate the target through fast neutron resonance radiography. By having a variety of source neutron energies, it is possible to take advantage of multiple attenuation resonances to differentiate between hydrogen, carbon, nitrogen, and oxygen [66].

This can be achieved either through a broadband pulsed spectrum neutron generator and time of flight measurements or kinematic reactions in an accelerator where neutron energy is dependent on the incident deuterium energy and the neutron emission angle [23]. One such broadband pulsed time of flight system that was developed initially had an explosive detection rate of 88 % with a false alarm rate of 2 %, which was improved to 93 % and 3.4, respectively [67, 68]. Additionally, the creation of a novel integrative detector that uses a plastic fiber scintillator screen has enhanced fast neutron energy discrimination via improved TOF measurements [69]. The kinematic method has also shown promise in simulations, but proven difficult in practice due to excessive secondary gamma ray contamination from the neutron source [70]. Both fast neutron resonance radiography methods also require relatively complicated accelerators and implementation [65].

Alternative and combined technologies

Many of the previously discussed methods of neutron interrogation have been adapted and applied to landmine detection. Several groups have looked at the ability of hydrogen rich explosives to thermalize fast neutrons and backscatter them [62, 71, 72]. When scanning a location for a possible landmine with a neutron flux, the higher concentration of backscattered neutrons from hydrogen in the landmine indicates its presence. Several detectors have been designed specifically for this application and shown some success [73–75].

Recently, several explosive detection systems have been designed or built that incorporate both the more traditional X-ray inspection systems and active neutron interrogation systems [76–78]. A system has already been deployed for field testing in the port of Rijeka in Croatia which uses X-ray images to determine any suspicious objects within a large cargo container. If an object raises concern, then a D-T neutron source is used to interrogate that particular area. It uses "tagged" neutrons and API to determine the time between creation of the initial neutron and the detection of FNA characteristic gamma rays [77]. In a different study, it was shown that by looking at the FNA peaks for oxygen and carbon as well as the neutron transmission peak, the explosive Semtex 1A was distinguished from other organic materials, provided the density of the target was known [31].

Another system under development aims to combine any number of interrogation techniques to obtain information. This method could use TNA, FNA, and NES in conjunction with gamma ray transmission to obtain information about the target and then compare that information to a library of threat templates that have already been analyzed and stored in its memory [79]. A different system is trying to use a cylindrical inertial electrostatic device, which is capable of creating D-T and D–D neutrons and 80 keV x-rays as a line-like source. By combining line source TNA and PFNA with x-ray interrogation, the system hopes to decrease scan time and false alarm rates associated with neutron beams [80]. A different experiment, first simulated with a Monte Carlo numerical code, found that by observing the slowing down of fast neutrons by hydrogen, the scattering of fast neutrons by carbon, nitrogen, and oxygen, and the Compton scattering of gamma rays due to the object's density provide three useful indicators as to the composition of the object [81]. Development is continuing on a portable active neutron interrogation system that utilizes D-T and D–D generators for TNA and FNA, with comparisons of laboratory benchmark measurements to Monte Carlo simulations [82]. Combining signals from fast and inelastic neutron scatter is also being investigated [83, 84].

Although systems designed to search for illicit nuclear material is beyond the scope of this work, the active neutron interrogation methods discussed here can also be applied to that mission. When irradiating a target to search for conventional explosives, the neutrons may also stimulate the release of characteristic radiation from special nuclear material. If the system is properly calibrated, these signatures can be detected as well [76, 82, 85]. This dual use encourages increased deployment while minimizing the cost and expense of fielding multiple systems.

Feasibility of explosive detection using neutrons

In a review published by the National Academy of Sciences (NAS), it was suggested that the X–ray screening systems already in place at airports were currently sufficient for explosive detection and it was recommended that a working prototype pulsed neutron system for luggage interrogation not be constructed [86]. The abilities of the system were no better than the x-ray method while the cost and size made implementation impractical. However, the report does suggest further laboratory research so as to be prepared for any new explosive detection challenges that may arise. It has been suggested that the use of a fast neutron interrogation system may be better suited for application as a second or third tier screening device [38]. Only after a possible threat had been identified by x-ray screening would the package be interrogated. Therefore, each package would have more time to be examined, which would lead to better results. Also, the number of systems, and hence the price of implementing them, could be reduced since the number of packages screened would not be as large.

Conclusion

Advances in active neutron interrogation steadily continue. Various aspects of the systems, such as neutron generators, electronics, signal acquisition, and analysis algorithms, are improving [30]. Furthermore, the cost and size of neutron and gamma ray detectors will continue to decline. This allows for cheaper and expanded deployment of neutron interrogation based explosive detection systems.

For further improvement, several of the methods can be combined. If PFTNA can be combined with FNSA, both the inelastically and elastically scattered neutrons contribute a signal. This is a more efficient use of the neutron source, and as a result, fewer neutrons would be needed to determine if a target is a threat. These methods could be used in conjunction with non-nuclear based devices to reduce the required neutron flux further. This would increase the throughput of the system while reducing the amount of activation and potential dose. Additionally, the lower neutron flux would require less shielding, reducing the weight and size of the system.

Active neutron interrogation systems are an interesting alternative to other explosives detection methods. Their unique approach allows for detection of explosives that other systems may miss due to high density shielding or disguised contraband. However, they cannot detect all explosives or other illegal items, such as guns and knives. As the technology continues to improve, active neutron interrogation should be further explored as a possible replacement detection method or solution to new, unique problems.

Acknowledgments The authors would like to thank Adrienne Lehnert and Tomasz Zak for their assistance in locating sources for this paper. This research was performed under appointment to the Department of Homeland Security (DHS) Scholarship and Fellowship Program, administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the U.S. Department of Energy (DOE) and DHS. ORISE is managed by Oak Ridge Associated Universities (ORAU) under DOE contract number DE-AC05-06OR23100. All opinions expressed in this paper are the authors' and do not necessarily reflect the policies and views of DHS, DOE, or ORAU/ORISE.

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